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THE EFFECT OF DIAMETER ON THE EFFORT REQUIRED TO ROTATE HANDWHEELS USED AS CRANKS

A Thesis
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ABSTRACT

The widespread use of handwheels in industry for the primary control of a wide variety of machine tools makes the proper design of these wheels a matter of importance. This experiment, designed to provide basic useful data in connection with this problem, was performed in the Motion and Time Study Laboratory at Purdue University.

Five handwheels ranging in diameter from four to fourteen inches were used by eight operators to overcome seven frictional torques ranging from three to sixty inch-pounds. The torques were applied by means of a prony brake. The rate of oxygen consumption by the operators was measured by a Sanborn EIS Metabolism Tester, and these measurements were used as the basic data from which the conclusions of the experiment were formulated.

Analysis of the data indicated that, within the limits of the ranges of the handwheel sizes and frictional torques used, the rate of human energy expenditure decreases with increased diameter of the handwheels.

The statistical analysis of the data indicated that the use of the Sanborn EIS Metabolism Tester is a satisfactory method for measuring human energy expenditure at relatively high levels.

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THE EFFECT OF DIAMETER ON THE EFFORT REQUIRED TO ROTATE HANDWHEELS USED AS CRANKS

INTRODUCTION

The proper design of any mechanical devices which are to be used manually must of necessity include consideration of many physical factors, some of the more important being size, weight, handle type and relative positioning with respect to the operator. The specification of the ultimate physical dimensions which the finished device will have is for the most part directly related to the use to which the device will be put. The criteria for successful performance are varied, and the extent to which the design is considered successful depends on which criterion or combination of criteria the designer feels is the most important to optimize. A brief list of some of the more important criteria would include cost, speed of operation, ease of operation, accuracy of operation, safety of operation, consistency of operation, force delivered, power delivered, etc. The ease of operation or effort required by the operator to rotate handwheels under various conditions of torque loading will be the main concern of this thesis.

Consideration of the various physical factors involved in the design of handwheels will be limited solely to consideration of the proper diameter. To attempt to consider all

the factors would be outside the scope of one thesis.

In the past, little consideration has been given to the proper dimensioning of handwheels in spite of their widespread application on most types of machine tools. In many instances the handwheels used have been much too small to effectively overcome the torques applied and in many cases the wheels have been unnecessarily large. Little information is available as to proper handwheel diameters from the standpoint of energy expenditure on the part of the operator. The main reason for this has been the lack (until recent years) of a suitable method of measuring the amount of energy a person expends while performing a given task. Measurement of the work done in foot pounds does not give the answer, since much depends upon the manner in which the work is performed, the conditions under which it is performed, and the characteristics of the operator performing the work. A person may himself work extremely hard and yet accomplish a relatively small amount of work as measured on the output end.

The reduction of the effort required by an operator to perform a given task is of prime concern to both labor and management, since such reductions are reflected in lower costs and higher quantity of production. This becomes especially important when highly repetitive jobs are considered. A machine tool operator, tending several

machines simultaneously, manipulates the machine controls many times in the course of a normal working day. Decreasing the operator's energy expenditure is almost certain to increase his effectiveness.

As has been pointed out previously in this thesis, few methods are available for the absolute measurement of human energy expenditure. However, the measurement of body metabolism as a measure of human energy expenditure has been used with success in several previous investigations at Purdue University. Tilles established the fact that a standard medical metabolism tester will successfully discriminate between small changes in human energy output[1]. The Sanborn EIS Metabolism Tester was used in this experiment to determine differences in energy requirements with respect to the diameter of several handwheels.

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1. TILLES, SEYMOUR, "An Investigation of the Suitability of the Sanborn EIS Metabolism Tester to Basic Motion Study Experimentation", Master of Science Thesis, Purdue University, Lafayette, Indiana, 1949.

EXPERIMENTAL PROCEDURE

Design of Method and Apparatus

Purpose

The primary purpose of this experiment is the determination of the optimum diameter handwheel for a given torque load applied to a shaft, when the handwheel is used as a crank. The secondary purpose is to determine the maximum torque which an operator may reasonably be expected to overcome with a given diameter handwheel. The tertiary purpose is to obtain information about the Sanborn Metabolism Tester which may be of value to other investigators in the field of basic motion study, and to prove its reliability for use in connection with the measurement of relatively high level energy expenditure.

Method

In order to facilitate the analysis of the data, as many conditions were held constant as was feasible. The height of the work area (i.e., the center of the prony brake shaft) was held constant at forty-four inches from the floor. The plane of the handwheels was held constant at 0 degrees angle of inclination with the vertical. The ambient temperature was held constant at twenty-eight degrees Centigrade and the pace at which the operator worked was controlled as closely as possible to forty RPM.

Five handwheels at seven torque loads were

investigated so that each operator had a total of thirty-five tasks to perform. Doubtless the results of the experiment would have been of more value had it been possible to investigate a greater number of handwheels and a wider range of torques. Further, it was felt that the use of a larger number of subjects would have increased the reliability of the findings. However, both the number of operators and the number of conditions investigated were severely limited by the time required for gathering and processing the data.

There was no method available for determining the length of time that would be required for the physiological recovery for each operator from a test run. However, a pilot test run indicated that undue fatigue would not occur within the two hour time allotted for each group of test runs. Further, it was felt that since the experiment was designed as much as possible to coincide with conditions in industry where an operator works for much longer periods of time, any fatigue occurring would not have excessively adverse effects on the results. Behl found that an operator performing a simple task could be expected to work for approximately one hour before appreciable fatigue occurred[2]. The total working time for an operator during each two hour session was approximately thirty-six minutes.

[2] BEHL, JOHN, "Determination of the Effect of Performing a Simple Task Over a Prolonged Period on the Rate of Energy Expenditure", Master of Science Thesis, Purdue University, Lafayette, Indiana.

The effects of learning and operator skill were minimized as much as possible by completely randomizing the order in which each operator was presented with the different conditions of handwheels and torques. This had the desirable effect of eliminating any sequence effects which might creep in if a set pattern were developed. The following tables indicate the order in which the tasks were presented to each operator.

NOTE: In the tables which follow, each task is designated by two numbers separated by a dash. The first number indicates the handwheel diameter in inches. The second number indicates the applied torque in inch-pounds. Thus, for example, the number 5-40 indicates the 5-inch handwheel with 40 inch-pounds of applied torque.

Table 1

Operator Characteristics

Operator	Age	Height	Weight	Nationality
William Terbo	22	6'2"	160	American
Hans Coster	28	5'9-1/4"	176	Dutch
Joseph Nestory	23	5'10-1/2"	165	American
Herbert Fichman	31	5'11-1/4"	185	American
John Crosse	26	6'0"	165	British
Elmo Lindquist	39	5'10"	175	American
Marvin Adelberg	23	6'3"	195	American
Hakon Refsum	24	6'2"	190	Norwegian

Table 2

Sequence of Task Presentation to Operators

(Numbers within the table are tasks)

Operator:	NESTORY			COSTER		
Date:	18 Mar.	19 Mar.	23 Mar.	17 Mar.	20 Mar.	24 Mar.
	10-60	10-10	4-60	7-60	14-30	7-20
	7-3	10-30	10-40	7-10	5-3	4-50
	7-40	14-10	7-10	5-50	4-40	10-3
	5-10	10-50	10-20	4-10	14-10	10-60
	14-20	10-3	14-3	14-40	14-3	5-10
	5-50	7-50	5-3	5-60	4-30	10-20
	14-60	5-60	14-50	10-50	4-50	4-30
	4-10	7-60	14-40	7-30	14-60	10-10
	5-30	4-50	14-30	14-20	10-40	10-30
	4-3	5-40	4-30	4-60	5-40	5-30
	4-20	7-30	4-40	14-30	7-3	4-20
	5-20	7-20		7-40	5-20	

Operator:	TERBO			FICHMAN		
Date:	15 Mar.	16 Mar.	17 Mar.	3 Apr.	5 Apr.	6 Apr.
	5-30	4-60	4-30	4-30	10-10	4-60
	4-20	7-50	14-20	5-3	4-10	4-3
	14-10	10-20	14-60	4-40	5-40	10-30
	7-40	10-60	5-30	14-50	10-40	7-20
	7-60	14-3	5-60	5-20	14-30	7-30
	10-3	7-10	14-40	10-50	7-3	10-3
	7-20	4-10	10-10	5-60	5-10	7-60
	7-30	7-3	10-50	14-40	7-10	7-40
	10-30	15-30	5-20	5-30	14-3	14-10
	4-30	10-40	14-50	14-60	10-60	4-20
		5-40	4-40	14-20	10-20	5-50
		4-10	4-50	4-30	7-50	
			5-3			

Table 2 (Continued)

Sequence of Task Presentation to Operators

(Numbers within the table are tasks)

Operator:	GROSSE			LINDQUIST		
Date:	1 Apr.	2 Apr.	4 Apr.	7 Apr.	8 Apr.	9 Apr.
	4-3	4-10	4-20	10-10	7-40	4-20
	14-60	7-50	10-60	7-3	14-50	5-30
	4-60	4-30	10-30	5-40	4-60	10-30
	14-30	4-60	5-50	10-40	14-20	10-10
	5-10	14-10	7-30	14-60	7-30	4-3
	14-40	5-40	4-40	7-50	10-50	10-20
	5-30	10-10	10-3	4-3	5-60	4-10
	7-40	10-20	7-60	14-3	14-40	10-60
	4-50	10-40	14-3	5-20	4-10	10-3
	10-50	5-20	7-20	4-40	5-50	4-50
	5-3	7-3	14-50	5-3	7-10	7-20
	14-20		7-10	14-30	7-60	

Operator:	REFSUM			ADELBERG		
Date:	3 Apr.	10 Apr.	11 Apr.	29 Mar.	9 Apr.	10 Apr.
	4-20	7-3	14-50	14-3	5-20	4-3
	10-30	5-40	4-60	10-30	4-30	4-60
	5-30	14-60	14-20	10-3	7-50	14-60
	10-10	7-50	10-50	7-30	5-60	14-30
	4-3	4-30	5-60	5-50	10-20	5-10
	10-20	14-3	5-50	7-20	4-10	14-40
	5-10	14-10	14-40	7-60	14-10	5-30
	10-60	4-40	4-10	7-10	5-40	7-40
	4-50	5-3	5-50	10-60	10-40	10-50
	7-20	14-30	7-10	4-20	7-3	4-50
	10-3	10-40	7-60	4-40	10-10	5-3
	5-20	7-40	7-30	14-50		14-20

Task

The tasks used consisted of cranking a handwheel mounted on the shaft of a prony brake. The speed used for all tasks was 40 RPM. The operator cranked from the standing position at a comfortable distance from the apparatus as shown in Figure 2. The distance from the apparatus at which the operator stood was left to the discretion of the operator. The operator cranked with his right hand and steadied himself by holding onto the left vertical upright of the prony brake with his left hand. Upon receipt of a verbal signal the operator began cranking and continued for three minutes, making one revolution for each two beats of a metronome set to oscillate at 80 beats per minute. The operator stopped cranking upon a second verbal signal. Upon completion of the task, the operator rested in a chair for five minutes while the handwheel and the torque were being changed for the next test run.

Each operator was given a total of thirty-five tasks, performed over a period of three separate days. These tasks covered every possible combination of handwheels and torques. Thorson found that there are no significant differences in oxygen consumption rates between identical tasks performed on different days[3]. From this it may be logically concluded that

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3. Thorson, P. J., "A Metabolic Investigation of One-Handed Versus Two-Handed Work", Master of Science Thesis, Purdue University, Lafayette, Indiana, August, 1951.

the differences between unlike tasks performed on different days should be constant. This constitutes the justification for spreading the tasks over three separate days.

Test Procedure

The tests were run in the metabolic room of the Motion and Time Study Laboratory at Purdue University. It was possible to bar this room from all persons with the exception of the operator and the writer. This was done in order to reduce the effect of random outside influences on the operator.

Prior to the first test run, each operator was completely briefed on the purpose of the experiment, the function of the prony brake, the function of the metabolism tester and the function of the metronome. Every precaution was taken to alleviate the nervousness induced by the metabolism tester. Following the briefing, the operator was given a trial test run in order to insure the complete understanding of the test procedure. All tests on all operators were governed by the following basic time schedule which was begun upon the arrival of the operator for the experiment.

Step	Time	Elapsed Time	Action
1	0-15	15 min.	Operator rested on cot. Just prior to the end of 15 minute period, the operator took a standing position facing the test apparatus. The nose clamp was adjusted and the rubber hose mouth piece was inserted in the operator's mouth.

Step	Time	Elapsed Time	Action
2	15-17	2 min.	The operator stood quietly breathing ambient air through the metabolism tester.
3	17-21	4 min.	The oxygen was turned on without the operator's knowledge and the operator began to breathe pure oxygen. This step constituted the basal or no work run. At the conclusion of this run, the operator was disassembled from the metabolic equipment and seated in a chair.
4	21-25	4 min.	Operator rested quietly in chair. Just prior to the end of the 4 minute rest period, the operator again took his position in front of the work area and was assembled to the metabolic equipment as in step 1 above.
5	25-26	1 min.	Operator stood quietly breathing ambient air through the metabolator.
6	26-27	1 min.	Operator began cranking the handwheel in time with the metronome while breathing ambient air through the metabolator. This constituted the warm-up period.
7	27-29	2 min.	Without the knowledge of the operator, the oxygen was turned on and the operator began breathing pure oxygen while continuing to crank in time with the metronome. At the conclusion of the two minute work period, the equipment was turned off and the operator disassembled from the apparatus and seated in the chair to rest.
8	29-34	5 min.	The operator rested in chair for five minutes while the handwheel and torque were being changed.

Steps 5 through 8 above, constituted a complete work-rest cycle of 9 minutes, of which 3 minutes were spent working and 6 minutes were spent resting. This work-rest cycle was repeated 12 times for each session in the lab. Following the completion of the final work-rest cycle, a second at rest basal test was run. Each complete session took about two hours and twenty minutes to complete and resulted in two basal tests and twelve working tests.

The selection of one minute for a warm-up period was based on the research of Behl, who showed that for a simple task, energy expenditure rises rapidly during the first minute of performance and does not change significantly for the next 64 minutes[4].

Equipment

1. The Sanborn EIS Metabolism Tester, shown in Figure 3, had the following essential elements:
   a. A synchronous motor which rotated the metal cylinder upon which the wax data chart was mounted.
   b. A spirometer bell which contained pure oxygen to be consumed by the operator.
   c. A metal pointer which inscribed the movement of the spirometer bell upon the wax chart.

[4] BEHL, JOHN, "Determination of the Effect of Performing a Simple Task Over a Prolonged Period on the Rate of Energy Expenditure", Master of Science Thesis, Purdue University, Lafayette, Indiana, 1950.

d. A two-way valve, whose function was the selection of either pure oxygen or ambient air for the operator's consumption.

e. A metabolime container, located inside the spirometer bell housing, had the function of filtering out the waste products of respiration, namely carbon dioxide and water vapor.

f. Nose clamp and rubber mouth piece whose function was the elimination of the possibility of ambient air entering the closed system formed by the operator and the metabolism tester.

2. The required frictional torques were obtained by means of prony brake especially designed for this experiment, and containing the following essential features: (See Figure 4)

a. A wooden frame constructed of 2" x 4" planks, 47 inches high by 20 inches wide.

b. A Sears and Roebuck Co. "Craftsman" 3/4 inch steel shaft and bearing mounts.

c. A maple wood wheel 3 inches thick with a radius of 2.578 inches. This wheel was mounted upon the steel shaft by means of two flanges containing 1/4 inch set screws.

d. Two Chantillon spring balances of 100 pound capacity, whose function was the rapid indication of the required frictional torque.

e. Two aluminum turnbuckles whose function was the rapid adjustment of the required frictional torque.

f. One nylon belt, 1-3/4 inches wide by 24 inches long, which, in conjunction with the polished wooden wheel, formed the friction element of the prony brake. A calibration curve for the prony brake appears in Appendix A.

3. The five cast iron handwheels which were investigated (See Figure 5) were standard industrial handwheels, and had the following characteristics:

Number	Diameter	Weight
1	4 inches	1.50 pounds
2	5 inches	2.00 pounds
3	7 inches	4.70 pounds
4	10 inches	10.00 pounds
5	14 inches	21.50 pounds

4. One Metronome De Maezel performed the function of pace indication for the operator (See Figure 4).

RESULTS AND CONCLUSIONS

Calculations

The basic data upon which the conclusions of this experiment were formulated were derived from the wax charts of the metabolism tester. The wax charts were wrapped around the metal cylinder which was driven at constant speed by the synchronous motor. The abscissa of the charts were the measure of elapsed time. As the operator inhaled, pure oxygen was breathed in from the spirometer bell causing the spirometer bell to fall. As the operator exhaled, the spirometer bell rose. This alternate rising and falling of the bell produced the peaked line on the wax chart. As each exhalation of the operator passed into the spirometer bell, the products of respiration were filtered out by the metabolime. Thus the spirometer bell rose to successively lower positions following each exhalation. This was indicated on the wax chart by successively lower peaks and was a measure of the rate at which the oxygen was being removed from the spirometer bell, and consequently a measure of the rate of oxygen consumption or energy expenditure by the operator.

Had the operator consumed oxygen at an absolutely constant rate, a straight line could have been passed through the successive peaks of the saw toothed graph on the chart. The slope of this line would measure the rate of oxygen consumption in cubic centimeters per minute. However, due to

the difference in volume of the operator's successive breaths, the respiratory cycle was not constant and the peaks did not fall into a straight line. It was therefore necessary to make the best possible approximation to a straight line by the method of least squares. A sample calculation of this method is shown in Appendix A, along with the steps necessary to convert the slope value to cubic centimeters of oxygen per minute. For the purpose of this thesis, it was not necessary to calculate the actual oxygen volume consumption since analysis of the slopes directly gave the required comparative information. In this connection, Wood has shown that corrections for temperature and pressure would be too small to have appreciable effect on the results, and therefore these corrections were not made[5]. The raw data for this thesis are deposited in the Motion and Time Laboratory at Purdue University.

[5] WOOD, J. F., "The Determination by Means of Metabolic Measurements of the Time Allowances to be Included Within Standard Rates for Jobs Partially Controlled by Machines", Master of Science Thesis, Purdue University, Lafayette, Indiana, 1951.

Table 3a.

SLOPE VALUES FOR EACH HANDWHEEL

DIAMETER

Torque = 3 inch pounds

Operator's Name	4 inch	5 inch	7 inch	10 inch	14 inch
TERBO	.419	.458	.471	.435	.505
COSTER	.288	.418	.337	.239	.318
EMSTORY	.334	.330	.337	.392	.336
FICHMAN	.405	.391	.400	.495	.453
CROSSE	.467	.462	.451	.390	.362
LINDQUIST	.359	.432	.422	.346	.407
ADELBERG	.479	.449	.443	.643	.616
REFSUM	.606	.549	.485	.575	.535
MEAN	.420	.436	.418	.439	.442
95% Conf. Limit of Mean	±.083	±.053	±.047	±.107	±.088

Table 3b.

SLOPE VALUES FOR EACH HANDWHEEL DIAMETER

Torque = 10 inch pounds

Operator's Name	4 inch	5 inch	7 inch	10 inch	14 inch
TERBO	.647	.536	.607	.499	.383
COSTER	.464	.530	.667	.495	.401
NESTORY	.500	.452	.432	.354	.396
FICHMAN	.803	.499	.606	.819	.575
CROSSE	.673	.606	.435	.543	.440
LINDQUIST	.744	.513	.634	.527	.477
ADELBERG	.818	.657	.496	.475	.620
REFSUM	.748	.692	.622	.697	.581
MEAN	.675	.561	.562	.551	.484
95% Conf. Limits of Mean	±.110	±.069	±.076	±.119	±.079

Table 3c.

SLOPE VALUES FOR EACH HANDWHEEL DIAMETER

Torque = 20 inch pounds

Operator's Name	4 inch	5 inch	7 inch	10 inch	14 inch
TERBO	.781	.895	.812	.624	.611
COSTER	1.099	.620	.787	.640	.509
NESTORY	.803	1.011	.536	.688	.448
FICHMAN	.977	.940	.553	.429	.635
CROSSE	.770	.848	.606	.587	.507
LINDQUIST	.818	.836	.596	.548	.606
ADELBERG	.992	.804	.849	.731	.591
REFSUM	2.186	.998	.647	.781	.752
MEAN	1.053	.869	.673	.629	.582
95% Conf. Limit of Mean	±.390	±.105	±.103	±.092	±.079

Table 3d.

SLOPE VALUES FOR EACH HANDWHEEL
DIAMETER

Torque = 30 inch pounds

Operator's Name	4 inch	5 inch	7 inch	10 inch	14 inch
TERBO	----	1.246	1.012	1.040	.671
COSTER	----	1.491	1.144	.790	.848
NESTORY	----	.971	.692	.566	.487
FICHMAN	----	.948	.535	.623	.728
CROSSE	1.467	.977	.938	.557	.658
LINDQUIST	----	2.368	.943	.632	.726
ADELBERG	1.370	.879	1.037	.752	.704
REFSUM	1.820	1.172	.910	.876	.873
MEAN	1.552	1.269	.901	.730	.712
95% Conf. Limit of Mean	----	±.123	±.164	±.140	±.100

NOTE: Blanks in the table indicate tasks which the operators were physically unable to perform in a satisfactory manner.

Table 3e.

SLOPE VALUES FOR EACH HANDWHEEL DIAMETER

Torque = 40 inch pounds

Operator's Name	4 inch	5 inch	7 inch	10 inch	14 inch
TERBO	----	1.340	.826	.753	.750
COSTER	----	1.372	1.564	1.088	.817
NESTORY	----	1.072	.753	.778	.698
FICHMAN	----	1.454	.743	.768	.611
CROSSE	----	1.406	1.007	.883	.633
LINDQUIST	----	1.020	1.050	.829	.825
ADELBERG	----	1.035	.924	.855	.643
REFSUM	----	1.822	1.128	.904	.991
MEAN	----	1.316	1.000	.857	.746
95% Conf. Limits of Mean	----	±.225	±.222	±.090	±.107

NOTE: Blanks in the table indicate tasks which the operators were physically unable to perform in a satisfactory manner.

Table 3f.

SLOPE VALUES FOR EACH HANDWHEEL DIAMETER

Torque = 50 inch pounds

Operator's Name	4 inch	5 inch	7 inch	10 inch	14 inch
TERBO	----	----	.989	.754	.797
COSTER	----	----	1.545	1.017	.807
NESTORY	----	----	.890	.712	.832
FICHMAN	----	----	.920	.874	.728
GROSSE	----	----	1.304	.730	.736
LINDQUIST	----	----	1.065	1.043	.748
ADELBERG	----	----	1.038	.850	.832
REFSUM	----	----	1.494	1.035	.684
MEAN	----	----	1.156	.877	.771
95% Conf. Limit on Mean	----	----	±.215	±.117	±.064

NOTE: Blanks in the table indicate tasks which the operators were physically unable to perform in a satisfactory manner.

Table 3g.

SLOPE VALUES FOR EACH HANDWHEEL DIAMETER

Torque = 60 inch pounds

Operator's Name	4 inch	5 inch	7 inch	10 inch	14 inch
TERBO	----	----	2.101	.971	.800
COSTER	----	----	1.389	1.046	.877
NESTORY	----	----	1.145	.858	.689
FICHMAN	----	----	1.211	.914	.730
CROSSE	----	----	1.413	.668	.897
LINDQUIST	----	----	1.093	.808	.805
ADELBERG	----	----	.992	.824	.807
REFSUM	----	----	1.381	1.124	1.094
MEAN	----	----	1.341	.902	.837
95% Conf. Limit of Mean	----	----	±.286	±.121	±.104

NOTE: Blanks in the table indicate tasks which the operators were physically unable to perform in a satisfactory manner.

Table 4.

MEAN* SLOPE VALUES FOR ALL TASKS

	HANDWHEEL DIAMETERS				
Torques	4 inch	5 inch	7 inch	10 inch	14 inch
3 in.lbs.	.420	.436	.418	.439	.442
10 in.lbs.	.675	.561	.562	.551	.482
20 in.lbs.	1.053	.869	.673	.629	.562
30 in.lbs.	----	1.269	.901	.730	.712
40 in.lbs.	----	1.316	1.000	.857	.746
50 in.lbs.	----	----	1.136	.877	.771
60 in.lbs.	----	----	1.341	.902	.837

*Each value in Table 4 is arrived at by taking the arithmetic average of the corresponding values for eight operators.

NOTE: Blanks in the table indicate tasks for which the operators were physically unable to perform in a satisfactory manner.

FORM F
APPROVED FOR USE IN
PURDUE UNIVERSITY

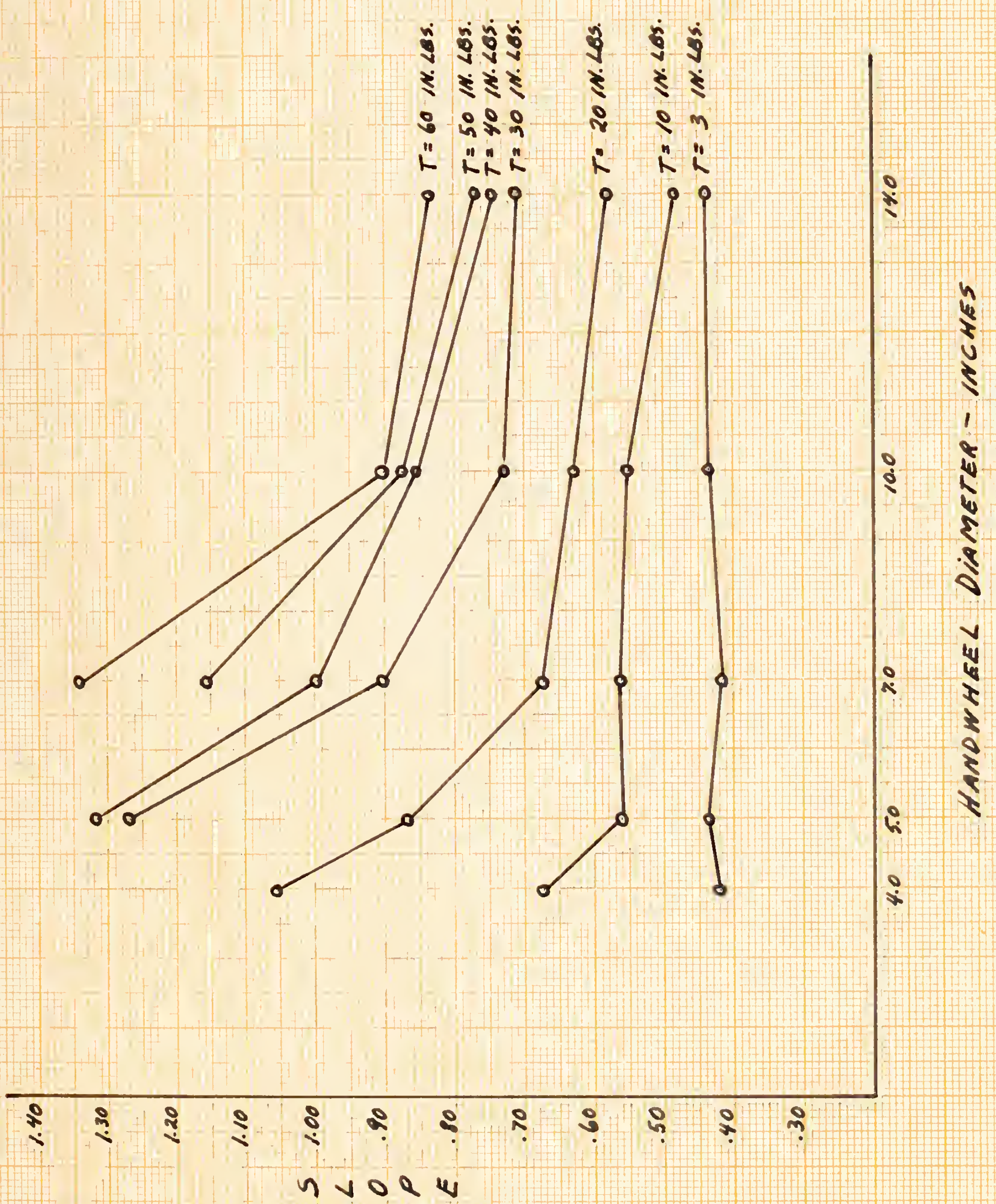

FIGURE 1 - TORQUE CURVES

Results

The data obtained for this experiment indicates that, with the exception of extremely small torque loads, the amount of energy expended cranking a handwheel decreases as the handwheel diameter is increased. However, the graphs of the data show a definite flattening out of the torque curves at the larger diameters. This would indicate that, for the torques investigated, the optimum diameter is approximately ten inches. Dr. Mundel and other investigators have indicated that the amount of energy expended by an operator depends to a large extent upon the muscle groups brought into use, the larger group requiring higher expenditure[6]. This phenomenon appears to be operative in this experiment. It would seem that the reduced energy expenditure resulting from the increasing mechanical advantage of the larger wheels (requiring reduced force application) gradually becomes balanced (and finally overcome) by the higher energy expenditure required by the use of the larger muscle groups of the upper arms, shoulder and torso. The gradual rise of the lowest torque curve added weight to this supposition.

The curves further indicate that handwheels smaller than 7 inches in diameter should not be used to overcome

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6. MUNDEL, M. E., Motion and Time Study Principles and Practice, p. 154, Prentice-Hall, Inc., New York, 1950.

torques in excess of 20 inch pounds (for continuous or high frequency repetitive operation), since to do so results in a high level of fatigue upon the operator. This was dramatically demonstrated by the inability of the operators to complete the test runs, using the smaller wheels, when torques in excess of 20 inch pounds were imposed. It was noted that, for the torque range between 30 and 60 inch pounds, the rate of decrease of energy expenditure with increased wheel size becomes very small. These break points which occur at the 10 inch wheel indicate that little is gained by increasing the wheel size much above this point.

The analysis of variance of the data showed significance at the 1% level for both wheels, torques, and wheels X torques, indicating that there was small probability that differences in the data could have occurred by chance. The interactions of wheels X operators and torques X operators had no statistical significance at the 5% level. This indicates that these causative effects were negligible and in fact did not cause significant differences in the slope values. However, the F test showed that the differences between operators was of significance at the 1% level of confidence. This was to be expected and could have been caused by any or all of several factors, some of the more probable being size, strength, rate of breathing, mental attitude and general condition of health of the operators.

No attempt was made to control the behavior of the subjects for the twenty-four hour period preceding the test. There is little reason to doubt that the activities of the subjects for the period preceding the tests had some effect on the data. Fortunately, this effect did not appear to be excessive and it is felt that it did little to impair the validity of the data.

The analysis of variance technique was used to evaluate the significance of the data[7]. The analysis was complicated by the fact that there were areas of missing data. It was found that the operators were physically incapable of cranking the 4 inch diameter handwheel for the required time interval, and at the required pace for torque loadings in excess of 20 inch pounds. A similar restriction was imposed on the use of the 5 inch diameter handwheel for torques in excess of 40 inch pounds. These areas of missing data precluded an analysis of the data as a whole. To solve this problem, the data was divided into two separate groups and an analysis of variance was conducted on each group. Group I data comprised all the slope values for torques 3, 10 and 20 inch pounds using all eight operators and all five handwheels. Group II data comprised the slope values for all seven torques, using all eight operators and handwheels of

7. LINDQUIST, E. F., Statistical Analysis in Educational Research, pp. 106-109, Houghton Mifflin Co., Boston, New York, Chicago, Atlanta, Dallas, San Francisco, 1940.

diameters 7, 10 and 14 inches respectively. The complete analysis of variance is indicated in Appendix A. The slope values are indicated in Tables 3a through 3g.

The 95% confidence limits for the means of the eight operators on each task were calculated using Student's t. These confidence limits are indicated in Tables 3a through 3g.

Conclusions

It may be concluded from this experiment that, to overcome torques in the range investigated, and with operator energy expenditure as the criterion, the larger diameter handwheels are more desirable.

For the torque range between 30 and 60 inch pounds the optimum diameter is at least ten inches.

For torques in excess of 20 inch pounds, handwheels of smaller diameter than seven inches are unsuitable.

It may be further concluded that the Sanborn EIS Metabolism Tester is a suitable device for making measurements of human energy expenditure at relatively high levels of performance.

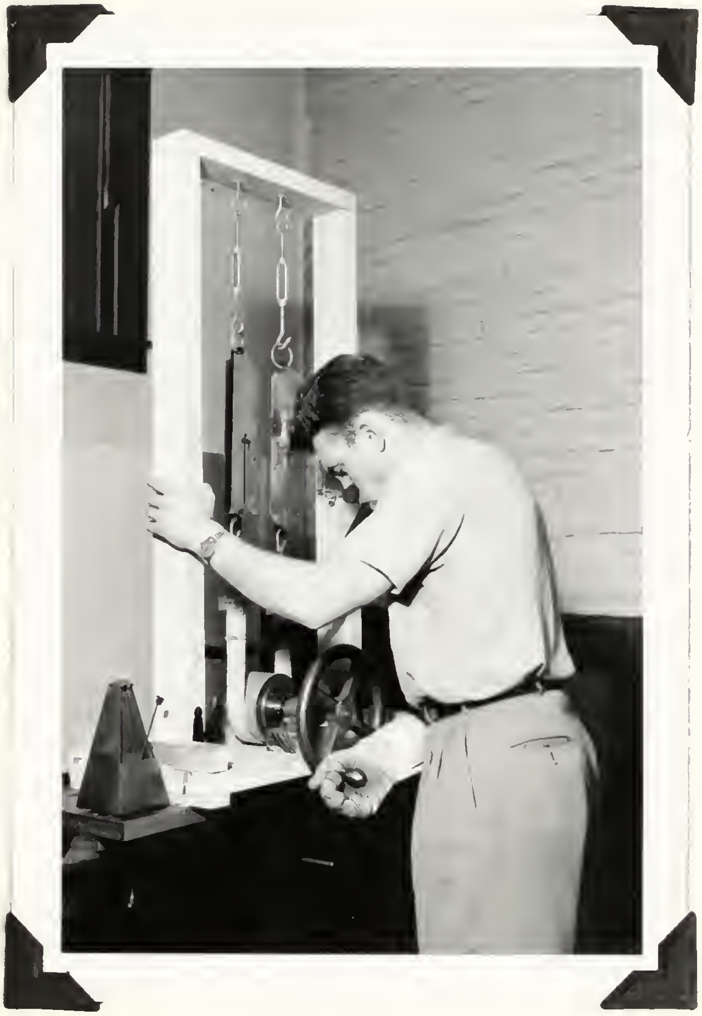


FIGURE 2

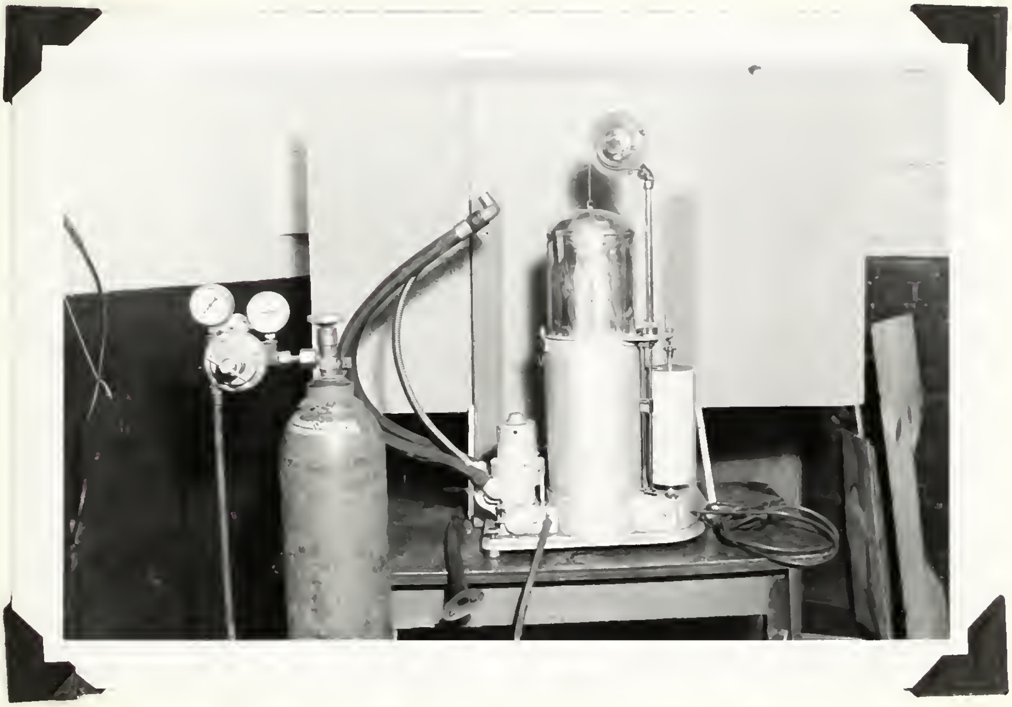


FIGURE 3

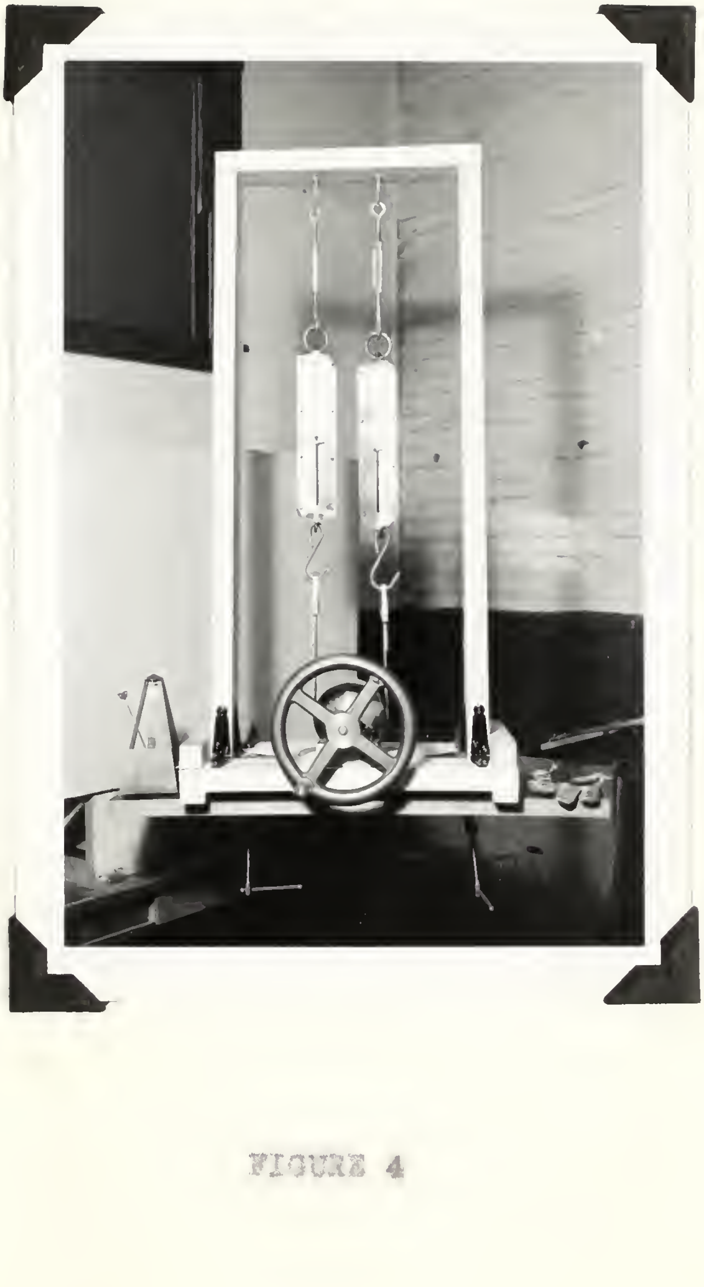


FIGURE 4

A [illegible]

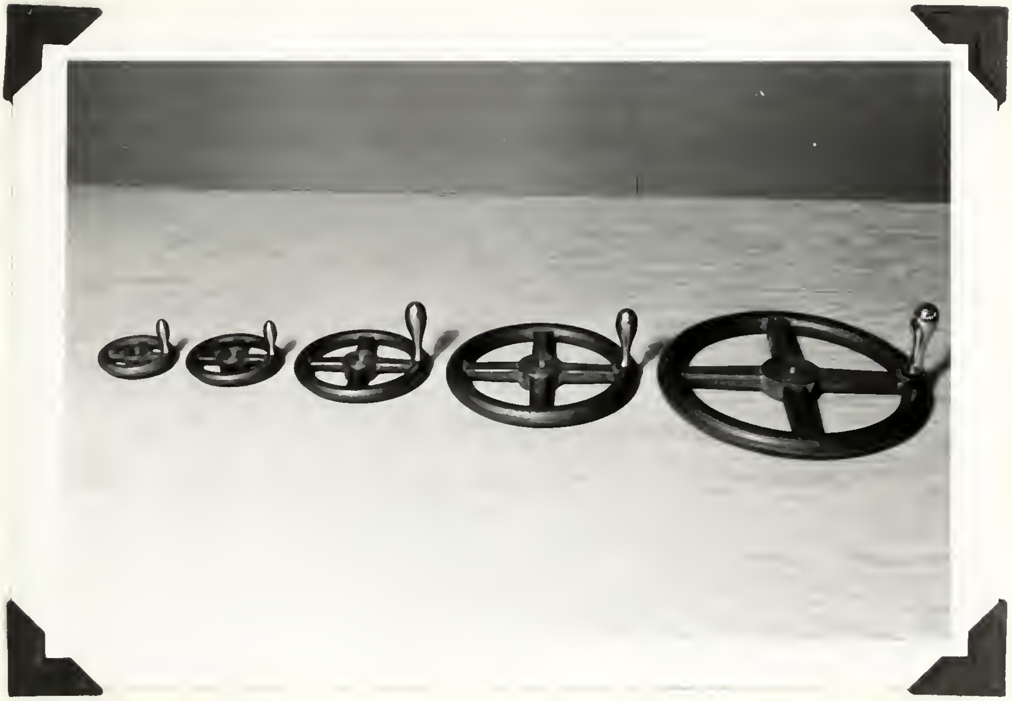


FIGURE 5

APPENDIX A

Discussion

The original intention had been to use the basal tests as a ground level from which to calculate the per cent increase of oxygen consumption of each test run over the no work condition. This idea was discarded after inspection of the basal tests indicated that little reliance could be placed on their reliability. The basals not only varied widely between operators but there was evidence of large random variation within each operator. In addition, it was noted that in several instances the values for the basal tests were higher than some of the lower level tasks. This was especially true of several of the low torque runs on the smaller handwheels. There are two possible explanations for this phenomenon. First, Tilles has shown that the Sanborn Metabolator gives results of low significance for light tasks involving finger movements of two or three inches.[8] Second, there is a definite possibility that an operator finds it more fatiguing to stand motionless for several minutes than to perform a very light task. To avoid introducing an additional possible source of error into the data, the basal tests were not used in the calculations. A sample wax chart and data sheet are included at the end of this appendix as an example of the calculations used for computing rate of oxygen consumption slopes.

[8] TILLES, SEYMOUR, "An Investigation of the Suitability of the Sanborn BIS Metabolism Tester to Basic Motion Study Experimentation", Master of Science Thesis, Purdue University, Lafayette, Indiana, 1949.

A rectangular coordinate system was imposed upon the wax charts and the X and Y coordinates of each peak of the saw tooth graph recorded. The slope of the best straight line which could be approximated was obtained from the following formula:

$$b = \frac{\Sigma X \Sigma Y - N \Sigma XY}{(\Sigma X)^2 - N \Sigma X^2}$$

where b = slope of line on wax chart in inches per inch

N = the number of peaks of the saw toothed graph

X, Y = rectangular coordinates of the peaks of the saw toothed graph.

On the wax charts a line with a slope of 1.000 represents 854.5 cubic centimeters of oxygen per minute. Therefore, the volume of oxygen consumed per minute for a given task is readily calculated by multiplying the appropriate slope by 854.5.

Cubic Cm. per minute = b x 854.5

Analysis of Variance Calculations

GROUP I ANALYSIS: This group comprises all the slope values for torques of 3, 10 and 20 inch pounds, using eight operators and five handwheels.

Table 5a.

Operator	Handwheel	4"	5"	7"	10"	14"
TERBO:	T=3 in.lbs.	.419	.456	.371	.435	.505
	T=10 " "	.647	.536	.607	.499	.383
	T=20 " "	.781	.895	.812	.624	.611
COSTER:	T=3 in.lbs.	.288	.418	.337	.259	.318
	T=10 " "	.464	.530	.667	.495	.401
	T=20 " "	1.099	.620	.787	.640	.509
NESTORY:	T=3 in.lbs.	.334	.330	.337	.392	.336
	T=10 " "	.300	.452	.432	.354	.396
	T=20 " "	.803	1.011	.831	.658	.448
FICHMAN:	T=3 in.lbs.	.405	.391	.400	.495	.453
	T=10 " "	.803	.499	.606	.819	.575
	T=20 " "	.977	.940	.553	.429	.635
CROSSE:	T=3 in.lbs.	.457	.462	.451	.390	.362
	T=10 " "	.673	.606	.435	.543	.440
	T=20 " "	.770	.848	.606	.587	.507
LINDQUIST	T=3 in.lbs.	.359	.432	.422	.346	.407
	T=10 " "	.744	.513	.634	.527	.477
	T=20 " "	.816	.836	.596	.548	.606
ADELBERG:	T=3 in.lbs.	.479	.449	.443	.643	.616
	T=10 " "	.818	.657	.496	.475	.620
	T=20 " "	.990	.804	.849	.731	.591
REFSUM:	T=3 in.lbs.	.606	.549	.485	.573	.535
	T=10 " "	.748	.692	.622	.697	.581
	T=20 " "	2.186	.998	.647	.761	.752
	TOTALS =	17.176	14.926	13.226	12.952	12.064

$GT(X) = 70.344 = T$ $GT(X^2)=47.511624 = \sum_{w,t,o} X^2_{wto}$

Table 5b.

HANDWHEELS

Operators	4"	5"	7"	10"	14"	T_o
TERBO	1.847	1.889	1.890	1.553	1.449	8.683
COSTER	1.751	1.588	1.791	1.374	1.228	7.812
NESTORY	1.637	1.793	1.300	1.434	1.180	7.344
FICHMAN	2.185	1.830	1.559	1.743	1.663	8.980
CROSSE	1.910	1.916	1.492	1.520	1.309	8.147
LINDQUIST	1.919	1.781	1.652	1.421	1.490	8.263
ADELBERG	2.287	1.910	1.788	1.849	1.827	9.661
REFSUM	3.540	2.239	1.754	2.053	1.868	11.454
T_w =	17.176	14.926	13.226	12.952	12.064	70.344 = T

NOTE: Each cell in Table 5b is T_{wo}. Value for each is arrived at by summing three torque values for each wheel-operator combination in Table 5a.

EXAMPLE: 1.847 = .419 + .617 + .781

Table 5c.

TORQUES

	3 in.lbs.	10 in.lbs.	20 in.lbs.	T_o
TERBO	2.288	2.672	3.723	8.683
COSTER	1.600	2.557	3.655	7.812
NESTORY	1.729	2.134	3.481	7.344
FICHMAN	2.144	3.302	3.534	8.980
CROSSE	2.132	2.697	3.318	8.147
LINDQUIST	1.966	2.895	3.402	8.263
ADELBERG	2.630	3.066	3.965	9.661
REFSUM	2.750	3.340	5.364	11.454
T_t =	17.239	22.663	30.442	70.344 = T

NOTE: Each cell in Table 5c is T_{to}. Value for each is arrived at by summing five wheel values for each torque-operator combination in Table 5a.

EXAMPLE: 2.288 = .419 + .458 + .471 + .435 + .505

Table 5d.

TORQUES

Handwheels	3 in.lbs.	10 in.lbs.	20 in.lbs.	T_w
4"	3.357	5.397	8.422	17.176
5"	3.489	4.485	6.952	14.926
7"	3.346	4.499	5.381	13.226
10"	3.515	4.409	5.028	12.952
14"	3.532	3.873	4.659	12.064
T_t:	17.239	22.663	30.442	70.344 = T

Table 5e.

Item	Source of Variation	df.	SS	Mean Square	F TESTS Source	F_{ob}	$F_{.05}$	$F_{.01}$
A	Wheels 1-5	4	.681927	.170482	A/E	9.10	2.71	4.07
B	Torques 1-3	2	2.202099	1.101049	B/F	53.14	3.74	6.51
C	Operators 1-8	7	.776106	.110872	$\frac{C+G}{E+F}$	3.45	2.08	2.82
D	Wheels x Torques	8	.391780	.048973	D/G	1.98	2.11	2.84
E	Wheels x Operators	28	.524594	.018973	E/G	.76	1.77	2.28
F	Torques x Operators	14	.290063	.020719	F/G	.84	2.23	2.19
G	Error (WxTxO)	56	1.409402	.025168				
H	Total	119	6.275971	.052739				

(H) $$\text{Total SS} = \sum_{w,t,o} X^2_{wto} - \frac{T^2}{120}$$
$$= 47.511624 - \frac{70344^2}{120}$$
$$= 6.275971$$

$$\text{Sub Total SS}_{wo} = \sum_{w,o} \frac{T^2_{wo}}{3} - \frac{T^2}{120}$$
$$= \frac{129.654840}{3} - 41.235653$$
$$= 1.982627$$

(A) $$\text{Wheels SS} = \sum_{w} \frac{T_w^2}{24} - \frac{T^2}{120}$$
$$= \frac{1006.021928}{24} - 41.235633$$
$$= .681927$$

(C) $$\text{Operator SS} = \sum_{o} \frac{T_o^2}{15} - \frac{T^2}{120}$$
$$= \frac{630.176384}{15} - 41.235653$$
$$= .776106$$

(E) Wheels x
$$\text{Operators SS} = \text{Sub Total SS}_{wo} - \text{Wheels SS} - \text{Operators SS}$$
$$= 1.982627 - .681927 - .776106$$
$$= .524594$$

$$\text{Sub Total SS}_{to} = \sum_{t,o} \frac{T^2_{to}}{5} - \frac{T^2}{120}$$
$$= \frac{222.519604}{5} - 41.235653$$
$$= 3.268268$$

(B) $$\text{Torque SS} = \sum_{t} \frac{T_t}{40} - \frac{T^2}{120} -$$
$$= \frac{1737.510054}{40} - 41.235653$$
$$= 2.202099$$

(F) $$\text{Torque x Operators SS}_{to} = \text{Sub Total SS} - \text{Torque SS} - \text{Operator SS}$$
$$= 3.268268 - 2.202099 - .776106$$
$$= .290063$$

$$\text{Sub Total SS}_{tw} = \sum_{t,w} \frac{T^2_{tw}}{8} - \frac{T^2}{120}$$
$$= \frac{356.091674}{8} - 41.235653$$
$$= 3.275806$$

(D) Torque x Wheel SS = Sub Total SS_{tw} - Torque SS
- Wheel SS
= 3.275806 - 2.202099 - .681927
= .391780

(G) Error SS = Total SS - (WSS + TSS + OSS + W xTSS)
(+ W x OSS + T x OSS)

= 6.275971 - (.681927 + 2.202099 + .776106)
(+ .391780 + .524594 + .290063)

= 1.409402

GROUP II ANALYSIS: This group comprises slope values for seven torques, eight operators and three handwheels.

Table 6a.

OPERATORS*

	TOR.	1	2	3	4	5	6	7	8
W 7"	3	.471	.337	.337	.400	.451	.422	.443	.485
H	10	.607	.667	.432	.608	.435	.634	.498	.622
E	20	.812	.787	.536	.553	.606	.596	.849	.647
E	30	1.012	1.144	.692	.535	.938	.943	1.037	.910
L	40	.836	1.564	.753	.748	1.007	1.050	.924	1.128
S	50	.989	1.545	.890	.920	1.304	1.065	1.038	1.494
	60	2.101	1.389	1.145	1.211	1.413	1.093	.992	1.381
TOTALS		$X = 48.422$	$X^2 = 49.382920$						
10"	3	.435	.239	.392	.395	.390	.346	.643	.575
	10	.499	.495	.354	.819	.543	.527	.475	.697
	20	.624	.640	.688	.429	.537	.548	.731	.781
	30	1.040	.790	.569	.623	.557	.632	.752	.876
	40	.753	1.088	.778	.768	.883	.829	.855	.904
	50	.754	1.017	.712	.874	.730	1.043	.850	1.035
	60	.971	1.046	.858	.914	.668	.808	.824	1.124
TOTALS		$X = 39.877$	$X^2 = 30.839827$						
14"	3	.505	.318	.336	.453	.362	.407	.616	.535
	10	.383	.401	.398	.575	.440	.477	.620	.581
	20	.611	.509	.448	.635	.507	.608	.591	.752
	30	.671	.848	.437	.728	.658	.728	.704	.873
	40	.750	.817	.698	.611	.653	.825	.643	.991
	50	.797	.807	.632	.728	.736	.748	.832	.884
	60	.800	.877	.689	.730	.897	.805	1.807	1.094
TOTALS		$X = 36.590$	$X^2 = 25.579906$						

$$GT(X) = 124.889 = T\,;\; GT(X^2) = 105.802653 = \sum_{w,t,o} X^2_{wto}$$

---

* Because of space limitations it was necessary to assign numbers to the operators. The operators are numbered at the top of Table 6a in the same sequence as they were presented in the previous tables.

Table 6b.

WHEELS

OPERATORS	7"	10"	14"	T_o
1	6.828	5.076	4.517	16.421
2	7.433	5.315	4.577	17.325
3	4.785	4.351	3.686	12.822
4	4.973	4.922	4.460	14.355
5	6.154	4.358	4.233	14.745
6	5.803	4.733	4.594	15.130
7	5.779	5.130	4.813	15.722
8	6.667	5.992	5.710	18.369
T_w =	48.422	39.877	36.590	124.889 = T

NOTE: Each cell in Table 6b is T_{wo}. Value for each cell is arrived at by summing seven wheel values for each torque-operator combination in Table 6a.

EXAMPLE: 6.828 = .471 + .337 + .337 + .400 + .451 + .422 + .443 + .485

Table 6c.

TORQUES

		3 in. lbs.	10 in. lbs.	20 in. lbs.	30 in. lbs.	40 in. lbs.	50 in. lbs.	60 in. lbs.	T_o
O	1	1.411	1.489	2.047	2.723	2.339	2.540	3.872	16.421
P	2	.894	1.563	1.936	2.782	3.469	3.369	3.312	17.325
E	3	1.065	1.182	1.672	1.748	2.229	2.234	2.692	12.822
R	4	1.348	2.000	1.617	1.886	2.127	2.522	2.855	14.355
A	5	1.203	1.418	1.700	2.153	2.523	2.770	2.978	14.745
T	6	1.175	1.638	1.750	2.301	2.704	2.856	2.706	15.130
O	7	1.702	1.591	2.171	2.493	2.422	2.720	2.623	15.722
R	8	1.595	1.900	2.180	2.659	3.023	3.413	3.599	18.369
T_t:		10.393	12.781	15.073	18.745	20.836	22.424	24.637	124.889

NOTE: Each cell in Table 6c is T_{to}. Value for each cell is arrived at by summing three wheel values for each torque-wheel combination in Table 6a.

EXAMPLE: 1.411 = .471 + .435 + .505

Table 6d.

TORQUES

W H E	3 in. lbs.	10 in. lbs.	20 in. lbs.	30 in. lbs.	40 in. lbs.	50 in. lbs.	60 in. lbs.	T_w
E 7"	3.346	4.499	5.386	7.211	8.010	9.245	10.725	48.422
L 10"	3.515	4.409	5.028	5.839	6.858	7.015	7.213	39.877
S 14"	3.532	3.873	4.659	5.695	5.968	6.164	6.699	36.590
T_t:	10.393	12.781	15.073	18.745	20.836	22.424	24.637	124.889

NOTE: Each cell in Table 6d is T_{tw}. Value for each cell is arrived at by summing eight operator values for each torque-wheel combination in Table 6a.

EXAMPLE: 3.346 = .471 + .337 + .337 + .400 + .451 + .422 + .443 + .485

Table 6e.

Item	Source of Variation	df.	SS	Mean Square	F TESTS Source	F_{ob}	$F_{.05}$	$F_{.01}$
A	Wheels 3-5	2	1.332248	.666124	A/E	22.48	3.74	6.51
B	Torques 1-7	6	6.904787	1.150798	B/F	69.48	2.32	3.26
C	Operators 1-8	7	1.026198	.146600	$\frac{C+G}{E+F}$	5.36	2.31	3.31
D	Wheels x Torques	12	1.002360	.083530	D/G	4.37	2.38	3.48
E	Wheels x Operators	14	.414935	.029638	E/G	1.56	2.20	3.13
F	Torques x Operators	42	.695670	.016564	F/G	.88	1.59	1.93
G	Error (WxTxO)	84	1.585608	.018876				
H	Total	167	12.961806	.076156				

(H) Total SS $= \sum_{w,t,o} x^2_{wto} - \frac{T^2}{168}$

$= 105.802653 - 92.840847$

$= 12.961806$

Sub Total SS$_{wo}$ $= \frac{\sum_{w,o} T^2_{wo}}{7} - \frac{T^2}{168}$

$= 95.614228 - 92.840847$

$= 2.773381$

(A) Wheels SS $= \frac{\sum_w T^2_w}{56} - \frac{T^2}{168}$

$= 95.173095 - 92.840847$

$= 1.332248$

(C) Operator SS $= \frac{\sum_o T^2_o}{21} - \frac{T^2}{168}$

$= 93.867045 - 92.840847$

$= 1.026198$

(E) Wheels x
Operators SS = Sub Total SS$_{wo}$ - Wheels SS - Operators SS

$= 2{,}773381 - 1.332248 - 1.02698$

$= .414935$

Sub Total SS$_{to}$ $= \frac{\sum_{t,o} T^2_{to}}{3} - \frac{T^2}{168}$

$= 101.467502 - 92.840847$

$= 8.626655$

(B) Torque SS $= \sum_t T^2_t - \frac{T^2}{168}$

$= 99.745634 - 92.840847$

$= 6.904787$

(F) Torque
x Operators SS = Sub Total SS$_{to}$ - Torque SS - Operator SS

$= 8.626655 - 6.904787 - 1.026198$

$= .695670$

Sub Total SS$_{tw}$ $= \frac{\sum_{t,w} T^2_{tw}}{8} - \frac{T^2}{168}$

$= 102.080242 - 92.840847$

$= 9.23935$

(D) Torque x
Wheel SS = Sub Total SS_{tw} - Torque SS - Wheel SS

= 9.239395 - 6.904787 - 1.332248
= 1.002360

(E) Error SS = Total SS - (A ≠ B ≠ C ≠ D ≠ E ≠ F)

= 12.961806 - 11.376198
= 1.585608

Calculation of Confidence Limits of the Means

Conf. Limit
of Mean
(Task = 4-5)

$$= \frac{t_{.05} \times S}{\sqrt{N}} = \frac{2.36 \times .0993}{\sqrt{8}} = \underline{\neq}\ .083$$

Where $t_{.05}$ = Student's t at the 95% confidence level for N-1 = 7 degrees of freedom.

$$S = \text{Standard Error} = \sqrt{\frac{\Sigma X^2 - \frac{(\Sigma X)^2}{N}}{N-1}}$$

N = 8 = Number of operators

X = Value of slope for each operator.

SLOPE CALCULATION

Chart No. 000 Run No. Basal #3 Operator Lindquist

CHART VALUES

X	Y	X	Y
5	102	94	70
8	103	98	69
12	101	102	69
15	99	106	68
18	97		
21	96		
25	95		
28	93		
32	93		
35	91		
39	90		
42	89		
46	88		
49	87		
53	83		
56	83		
60	82		
64	80		
68	78		
71	80		
75	77		
79	77		
83	75		
87	74		
91	70		

$n = 29$

CALCULATED VALUES

ΣX 1562 $2\Sigma XY$ 245104

ΣY 2449 ΣX^2 110674

ΣXY 122552

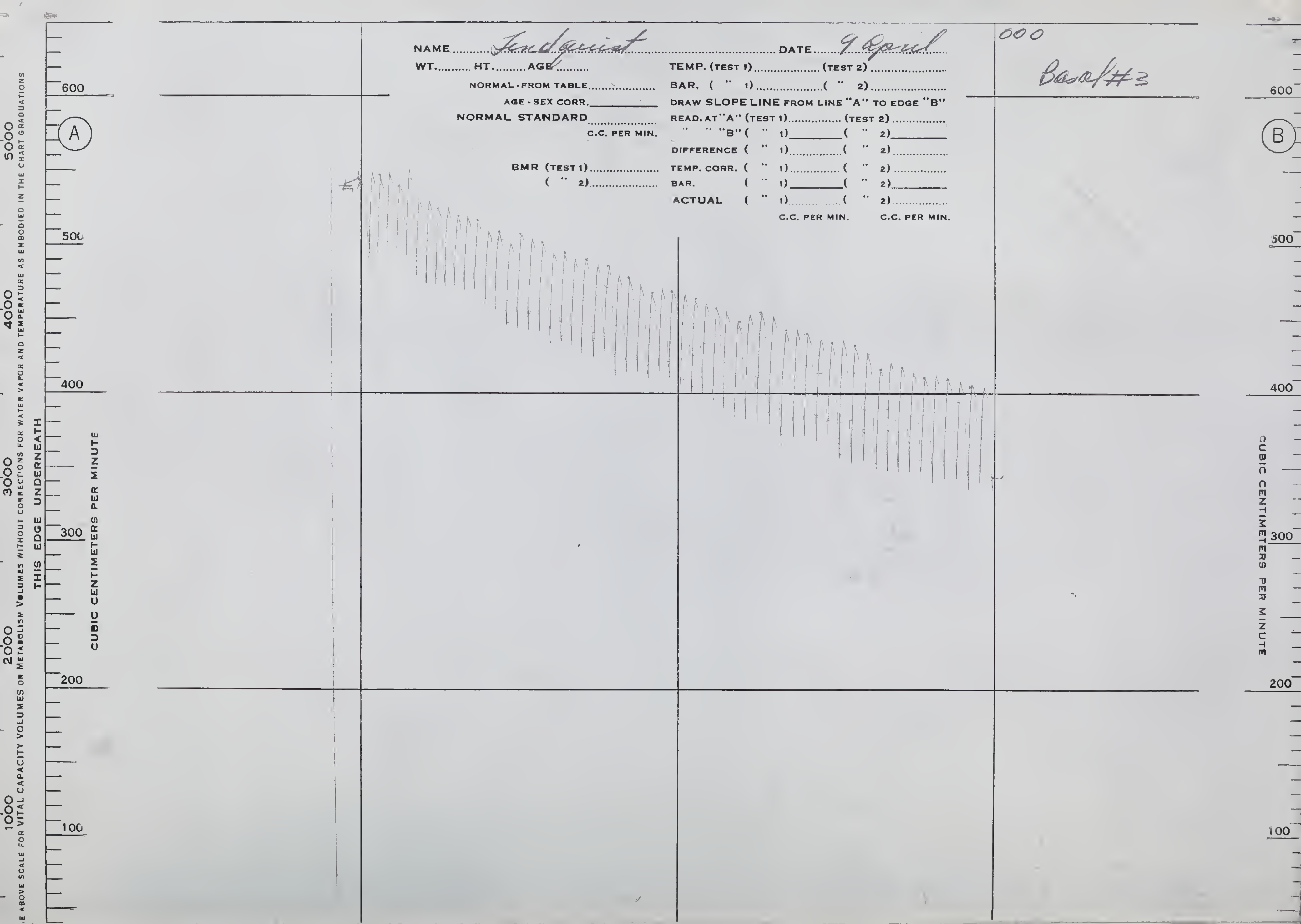
$N\Sigma XY$ ________

$\Sigma X \Sigma Y$ ________

$(\Sigma X)^2$ ________

$N\Sigma X^2$ ________

$$b = \frac{\Sigma X \Sigma Y - N\Sigma XY}{(\Sigma X)^2 - N\Sigma X^2} = \frac{271330}{769702} = .35251$$



NAME Lindquist DATE 9 April

WT. HT. AGE

NORMAL-FROM TABLE

AGE-SEX CORR.

NORMAL STANDARD

C.C. PER MIN.

BMR (TEST 1)

(" 2)

TEMP. (TEST 1) (TEST 2)

BAR. (" 1) (" 2)

DRAW SLOPE LINE FROM LINE "A" TO EDGE "B"

READ. AT "A" (TEST 1) (TEST 2)

" " "B" (" 1) (" 2)

DIFFERENCE (" 1) (" 2)

TEMP. CORR. (" 1) (" 2)

BAR. (" 1) (" 2)

ACTUAL (" 1) (" 2)

C.C. PER MIN. C.C. PER MIN.

000

Basal #3

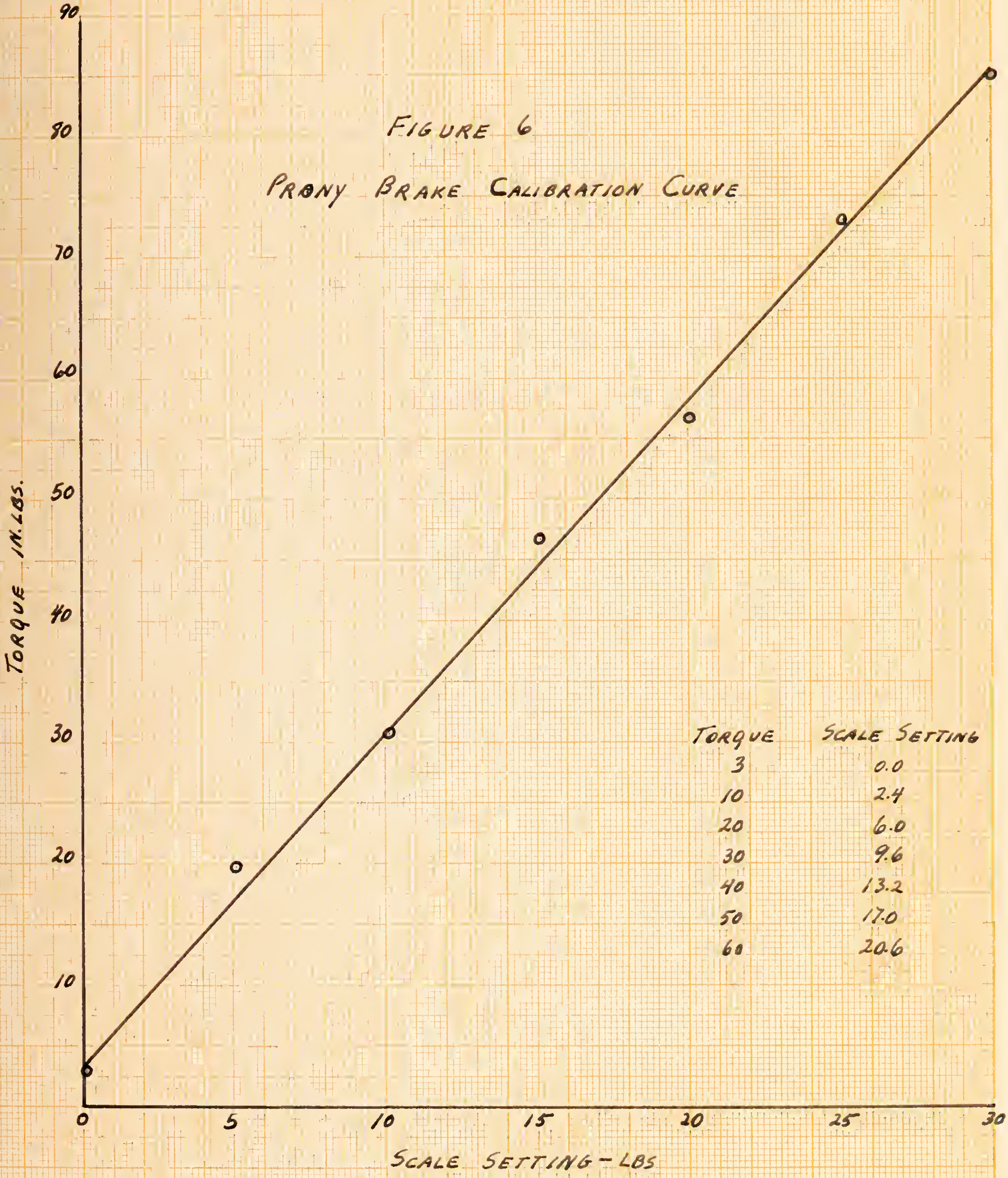


FIGURE 6

PRONY BRAKE CALIBRATION CURVE

TORQUE	SCALE SETTING
3	0.0
10	2.4
20	6.0
30	9.6
40	13.2
50	17.0
60	20.6

APPENDIX B

SUGGESTIONS FOR FURTHER EXPERIMENTATION

Sources of Error

Although the data of this experiment gave statistically valid results, certain variables did not lend themselves to close control, and each of these variables contributed in some degree to the total accumulated error in each test value. Some of the more important of these error sources are listed below, together with a suggested remedy.

1. Individual differences in the operators took various forms. Variations between the activities of operators for the twenty-four hours preceding the tests, variations in mental attitude (influenced by personal problems), variations in size, strength, age and health and, most important, variations in normal rate and depth of respiration, all had some effect upon the data. A striking example of the variations in rate and depth of respiration is demonstrated by comparison of the data for Hakon Refsum and Joseph Nestory. Refsum's average rate of respiration on the basal tests was seven inhalation-exhalation cycles per minute. Nestory's respiration rate on the same

tests was twenty cycles per minute. The rates were approximately constant from day to day. A closely controlled experiment in which operators of approximately the same respiratory rate and whose activities were supervised for the twenty-four hour period preceding the tests might, to some extent, eliminate this source of error.

2. It was noted that the instant of transfer of the operator from ambient air to pure oxygen had an influence upon the rate at which oxygen was expended from the spirometer bell. When the two-way valve was thrown at the beginning of an inhalation, the operator's lungs, on the first breath, were filled with pure oxygen, and the products of respiration consisted of O_2, CO_2 and H_2O, the latter two products being absorbed in the metabolime. When the valve was thrown at the beginning of exhalation, the products of respiration consisted of O_2, N_2, CO_2 and H_2O. Since the N_2 was not absorbed by the metabolime, it remained in the closed system formed by the operator and the spirometer bell, and subsequently reduced the rate at which the contents of the bell were expended, having a net effect of decreasing the observed

oxygen consumption rate slope. It is strongly recommended that future researchers take this phenomenon into account and avoid this source of error by timing the transfer to pure oxygen so that the transfer occurs at the beginning of an inhalation. This should eliminate the entrance of nitrogen into the system.

3. The capacity of the spirometer bell was insufficient for a complete two-minute run at the higher levels of activity. In several instances, the bell was almost wholly evacuated within one and a half minutes. This enforced the calculation of slope values using the fewer peaks on the wax chart, and it is probable that some error was introduced because of this.
4. Irregularities in respiration, such as excessively long or short breaths, caused high or low peaks on the saw tooth graphs and introduced inaccuracies in the calculation of the true slopes. This was particularly noticeable at the higher levels of performance when the operators were required to exert relatively large forces to keep pace with the metronome. Discussion of this phenomenon with the operators tended to reduce the effect to some degree. However, it is felt that this will always be a source of error in experiments of this nature.

Experimental Time Requirements

Listed below is an approximate breakdown of the time spent in getting the data for this thesis.

Construction and assembly of apparatus	80 hrs.
Preparation and conduction of test runs	56 hrs.
Calculation of slopes	140 hrs.
Statistical analysis	20 hrs.
Total	296 hrs.

It is apparent that excessive time was required for the calculation of the slopes. Each slope calculation involved determining and recording the rectangular coordinates for a saw tooth graph and then by the method of least squares determining the slope of the line of best fit. This procedure, which took approximately 30 minutes per graph, is so tedious as to preclude the use of the equipment to gather large quantities of basic motion data. Halberstadt has indicated that the time spent for conversion of the raw data to slope values may be greatly reduced by the use of an IBM system containing an IBM Calculator, IBM Duplicating Summary Punch and an IBM punched card system[9]. It is felt that the work of any investigator, possessing sufficient mechanical ability to construct such an IBM system, would be a considerable contribution to the field of metabolism experimentation.

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